

Motivation

Recent studies reveal an increased sensitivity of gradient related observations (strains, rotations and their time derivatives) to near surface structural heterogeneities (e.g., material contrast, cavities) compared to directly measured wavefields (and their time derivatives) [3]. The development of new sensing technologies, such as rotational ground motion sensors and distributed acoustic sensing (DAS), enable measurements of strain and rotations and motivate this study. Combining gradient related observations with ambient noise-based monitoring methods has the potential to increase both spatial and temporal resolution [2], [1]. The goal of this study is thus to assess the potential of rotational ground motions to resolve time-dependent near surface structural heterogeneities using noise correlations.

Calculation of Synthetic Data

In order to investigate the suggested benefits, we perform a numerical study in 2D, where we simulate seismic noise with random sources at random locations [Fig.1]. We apply interferometric principles and calculate cross-correlations (CC) of the resulting noise traces recorded at x_A and x_B for multiple realizations of the noise field. [Fig.2] shows 2D domains for a homogeneous reference (left hand panel) and a perturbed model (right hand panel) for further analysis of measurements. We specifically follow [3] for the definition of our model perturbation that is realistic if we consider the velocity contrast between granite and unconsolidated sediments.

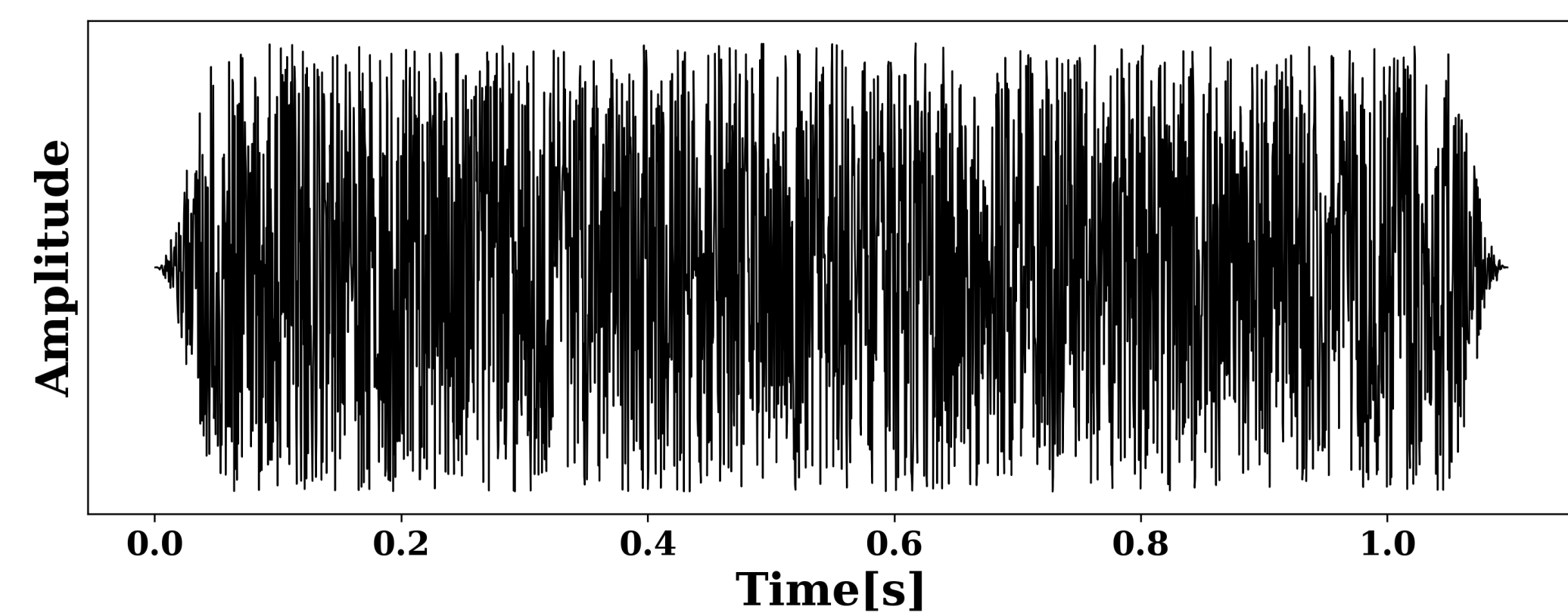


Figure 1. Random source time function to generate ambient seismic noise

After averaging multiple realizations, we expect to obtain symmetric CC functions. We first test the convergence of CC for a homogeneous reference [Fig.2 - left hand panel]. Thus, we compare the causal (+) and anti-causal (-) parts of the CC and we calculate the root mean squared (RMS) error. Symmetry comparison is based on varying number of stacks and simulation time length. With the results of the convergence test, we define the maximum number of stack and the longest time length of simulation as 1000 and 40s for further experiments, balancing accuracy of results and computational cost of simulation.

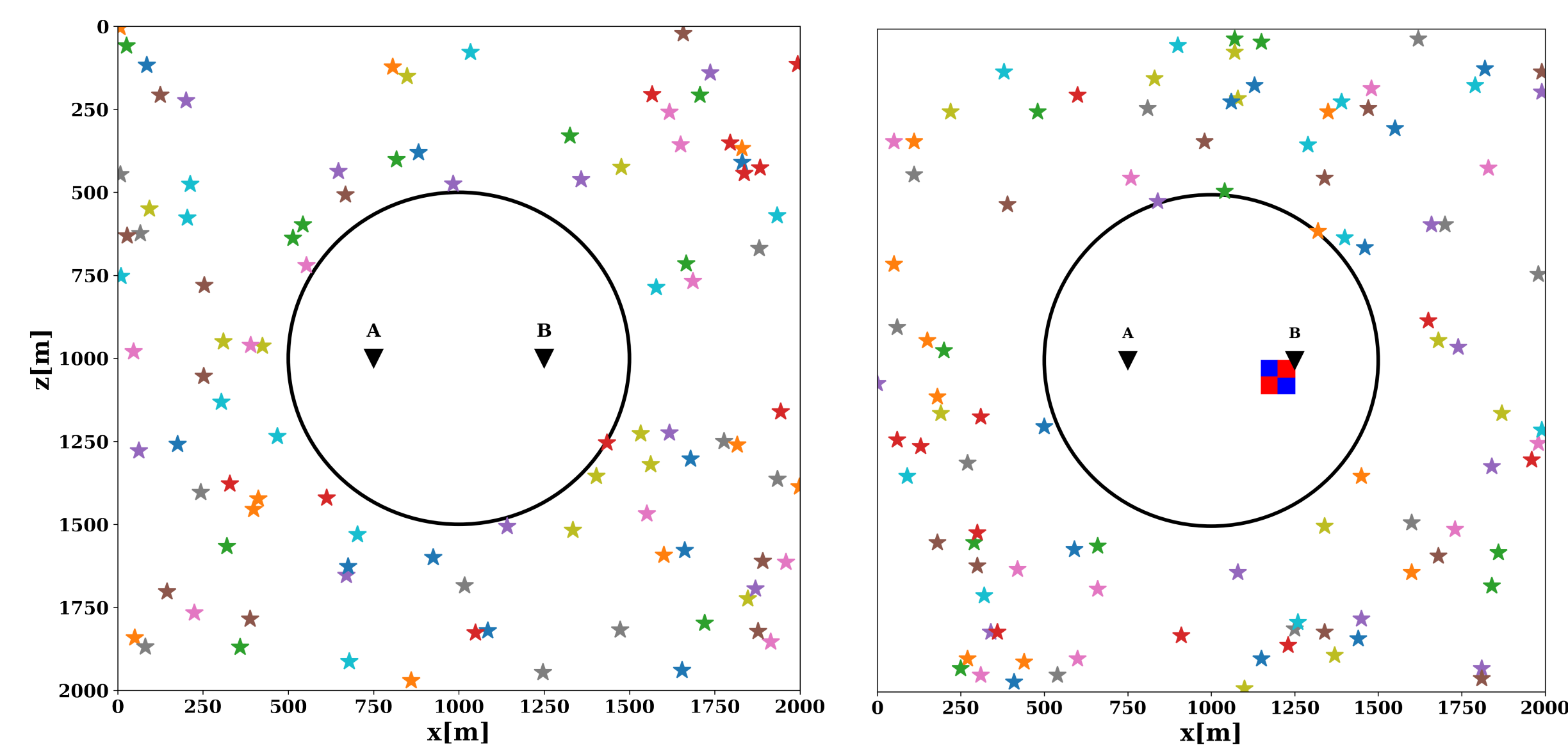


Figure 2. Left hand panel: a homogeneous reference with elastic model parameters; $v_p = 3000\text{m/s}$, $v_s = 1800\text{m/s}$, and $\rho = 2000\text{kg/m}^3$. Right hand panel: a perturbed model, heterogeneity is marked by square shape with area $100 \times 100 \text{ m}^2$ and it is separated into 4 cells. Each cell differs by -50% (blue) or $+50\%$ (red) from surroundings. All boundaries are reflecting. Noise sources are marked by stars and the receivers by triangles.

Convergence Test of Symmetric Correlation

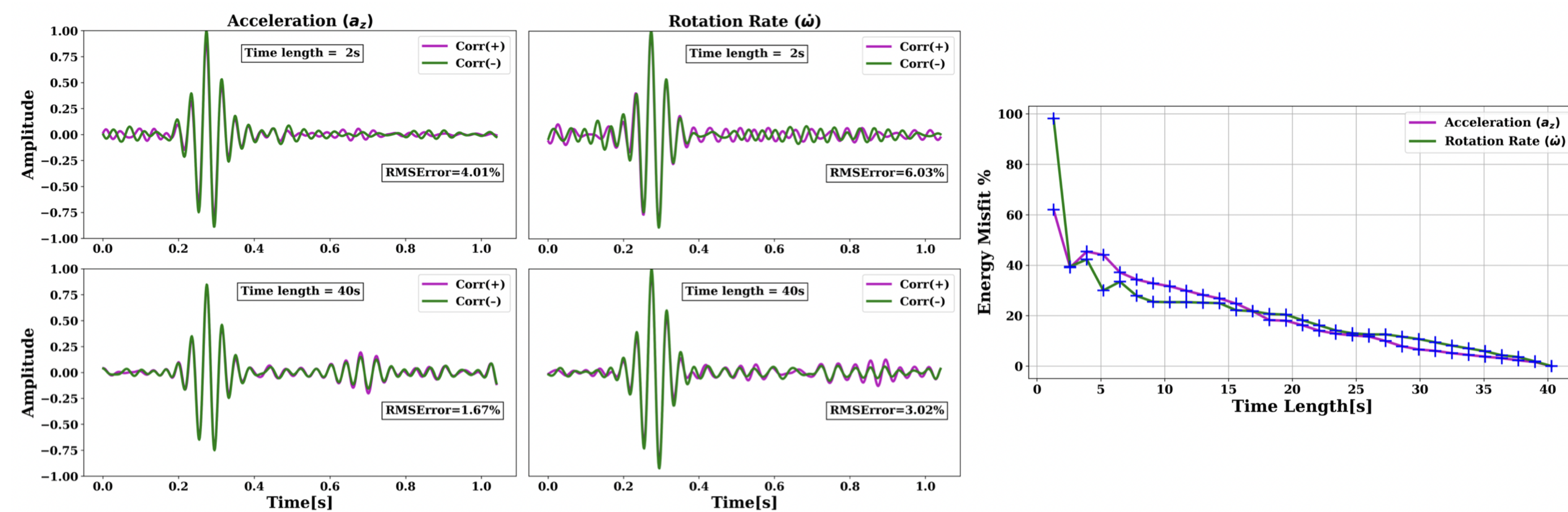


Figure 3. Symmetry of anti-causal(-) and causal(+) parts of 1s time window of stacked cross-correlations. Left hand panel: CC of acceleration and CC of rotation rate for number of realizations w.r.t varying simulation time lengths. Right hand panel: effect of increase in the time length of the recordings on the CC functions by energy misfit. Plus mark (+) indicates data used with varying time length.

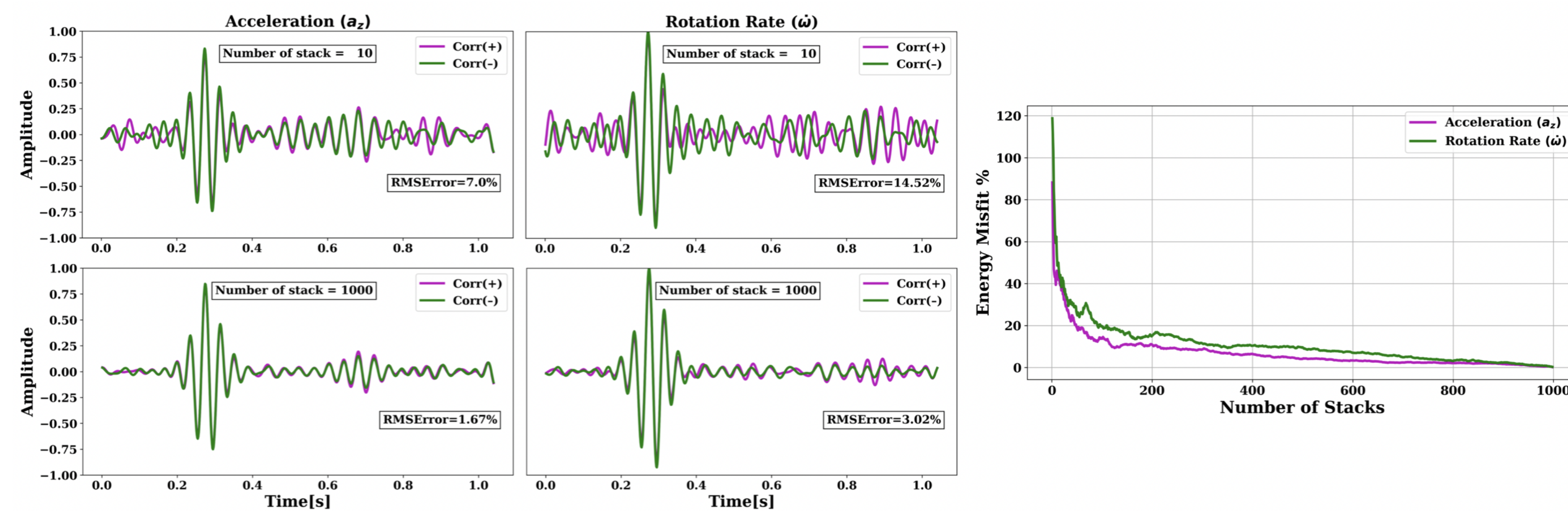


Figure 4. Symmetry of anti-causal(-) and causal(+) parts of 1s time window of stacked cross-correlations. Left hand panel: CC of acceleration and CC of rotation rate for increasing number of stacks. Right hand panel: effect of number of realizations on the CC functions by energy misfit.

Analysis of Model Perturbation

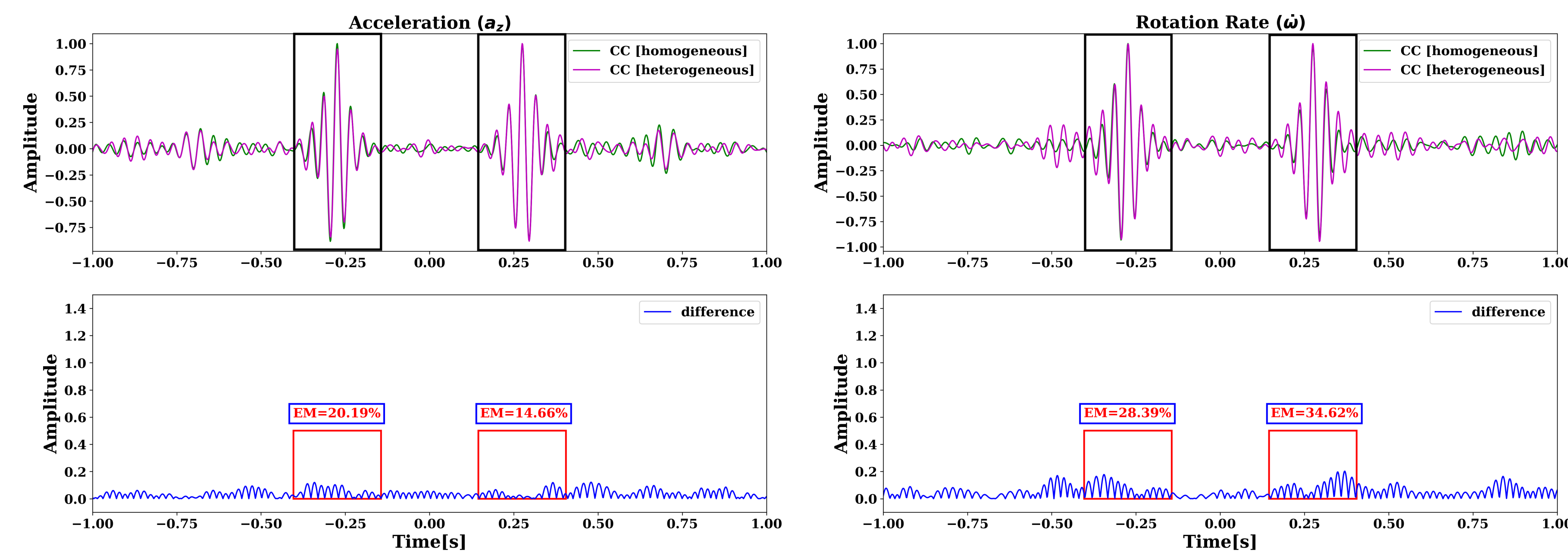


Figure 5. Energy misfit (EM) between CC of homogeneous model and heterogeneous model with model perturbation ($\pm 50\%$, $100 \times 100 \text{ m}^2$) and dominant frequency ($f_d = 20 \text{ Hz}$); for acceleration (left hand panel) and rotation rate (right hand panel)

Results

According to the results, [Fig.3] and [Fig.4] show an improvement of the CC functions with increasing simulation time length and number of stacks (on the left hand panels) respectively. We consider the CC function using maximum number of stacks as reference CC and we compute energy misfit between reference CC and CC with increasing number of stacks [Fig.4 - left hand panel]. Similarly considering the CC function with longest time length as reference CC, we also calculate energy misfit of the reference CC and CC with increasing time length [Fig.3 - left hand panel].

After analysing the convergence of the correlation functions in terms of simulation length and number of simulations, we compare noise correlations of acceleration and rotation rate for a homogeneous reference and a perturbed model [see Fig.5.].

MP	λ_d [m]	x [m]	λ_d/x	$\overline{EM}(\dot{\omega}) / \overline{EM}(a_z)$
+50%	200	36	0.18	1.15 %
+50%	100	36	0.36	1.22 %
±50%	100	90	0.9	1.80 %

Table 1. MP refers the model perturbation, λ_d/x is the ratio between dominant wavelength and size x of heterogeneity; $\overline{EM}(a_z)$, and $\overline{EM}(\dot{\omega})$ are averaged energy misfits for acceleration and rotation rate respectively.

Changing model perturbation and/or dominant frequency, we obtain the results of different models shown in Table 1. We represent these models by the proportionality (λ_d/x) for further comparison. We perform the following steps for both acceleration and rotation rate. We compute energy misfit between CC of homogeneous and CC of heterogeneous media for both causal (+) and anti-causal (-) parts of CC. $\overline{EM}$ here is averaged energy misfit of causal (+) and anti-causal (-) parts of CC. Then, we inspect results in terms of proportionality λ_d/x considering the ratio between $\overline{EM}(\dot{\omega})$ and $\overline{EM}(a_z)$. The last row of Table 1 shows the results for [Fig.5]. $\overline{EM}(\dot{\omega})/\overline{EM}(a_z)$ demonstrates an increased sensitivity of rotation rate compared to acceleration concerning calculated models.

Conclusion

Convergence test points out two effective parameters which are simulation time length and number of stacks to improve noise correlations. In this study, we confirm that longer simulation time lengths lead to an improved signal reconstruction in the correlation functions. In addition, multiple realizations help to suppress incoherent signals. Calculating a model with perturbed elastic media, we observe the effect of perturbation on the CC of acceleration and on the CC of rotation rate. Ultimately, we establish that noise correlations of wavefield gradients and/or their time derivatives are more sensitive to small-scale heterogeneity.

Discussion and Future Work

We study improvement of noise correlations and sensitivity of wavefield gradients to structural, small-scale heterogeneities. In accord with the results, including gradient related observations in ambient noise-based monitoring methods has the potential to improve their resolution capabilities. The scope of this study can be extended using different frequency bands, more realistic setups, e.g. 3D with sources at the surface, and improving the effective parameters (e.g., simulation time length, number of realizations, etc.) for noise correlations.

References

- [1] Nori Nakata, Lucia Gualtieri, and Andreas Fichtner. *Seismic Ambient Noise*. Cambridge University Press, 2019.
- [2] Patrick Paitz, Korbinian Sager, and Andreas Fichtner. Rotation and strain ambient noise interferometry. *Geophysical Journal International*, 216(3):1938–1952, 12 2018.
- [3] Sheha Singh, Yann Capdeville, and Heiner Igel. Correcting wavefield gradients for the effects of local small-scale heterogeneities. *Geophysical Journal International*, 220(2):996–1011, 10 2019.